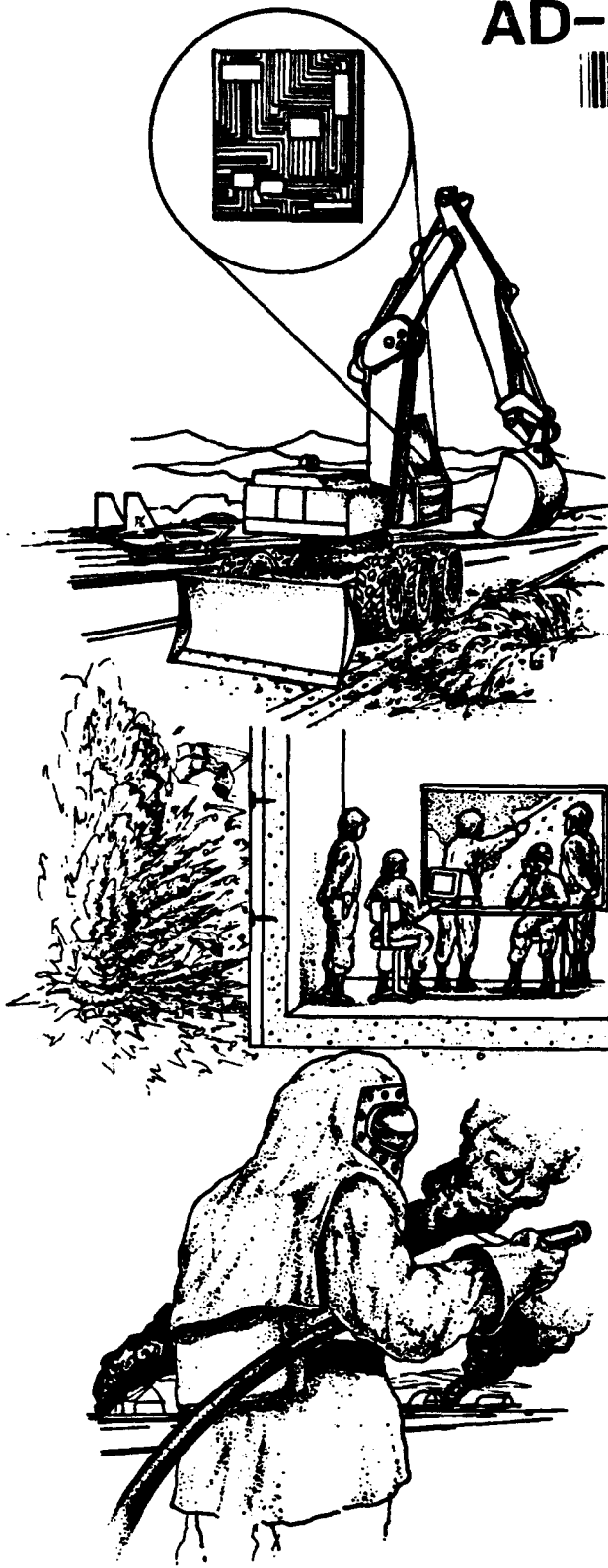


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AUTOMATED SHOTCRETE EQUIPMENT FOR EXPEDIENT REPAIR OF STRUCTURAL FACILITIES

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DECEMBER 1992

FINAL REPORT

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<p>High-Output, automated, remotely controlled shotcrete equipment for use in a dry-mixed shotcrete-based Expedient Repair of Structural Facilities (ERSF) system were investigated. The most promising piece of equipment was evaluated in the field at Tyndall AFB, Florida. Based on field evaluation results, an ERSF system to repair damaged and destroyed reinforced concrete walls, and other similar structural members, using dry-mixed shotcrete and commercially available shotcrete equipment is a viable concept.</p>					
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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this effort was to identify, then evaluate in the field, the most promising piece of high output, automated, remotely controlled shotcrete equipment for use in a shotcrete-based Expedient Repair of Structural Facilities (ERSF) system developed by the Air Force Civil Engineering Support Agency's Airbase Survivability Branch (AFCESA/RACS). Fielding of ERSF systems will improve the ability of Forward Operating Bases (FOBs) to fulfill their mission after attack by enhancing the Base Recovery After Attack (BRAAT) phase of the Airbase Operability (ABO) concept.

B. BACKGROUND

To fulfill its mission after an attack, an airbase must be able to quickly generate aircraft sorties, and then sustain them. To generate sorties, an airbase must have a usable and accessible runway surface. To sustain them, the airbase mission-critical facilities must be operational.

During the SALTY DEMO airbase survivability exercise in 1985, when Damage Assessment Teams (DATs) in the field informed the Damage Control Center (DCC) of a damaged mission-critical facility, the DCC could give them little or no guidance on how to repair the facility. This highlighted the fact that the Air Force did not have systems in-place at FOBs to expediently repair mission-critical facilities. Without such a capability, airbase mission fulfillment is jeopardized. Consequently, an Expedient Repair of Structural Facilities (ERSF) system development effort was undertaken by AFCESA/RACS. The work documented in this report is part of this ERSF system development effort.

C. SCOPE

Commercially available automated shotcrete equipment was investigated, and the most promising candidate piece of equipment was evaluated in the field at the Tyndall AFB, Florida SKY X test range. Based on this field

evaluation, recommendations for full-scale development and fielding of a shotcrete-based ERSF system were made.

D. RESULTS

Candidate shotcrete equipment that appears suitable for use in an ERSF system is commercially available in the tunneling and mining industries. The manufacturers of such equipment are mostly foreign. Two foreign companies who market their equipment in the United States were identified: Aliva Ltd. (marketed by Surecrete, Inc. in the U.S.), and Meyco Ltd. (Marketed by Master Builders Technologies in the U.S.). An Aliva Spray Boom 80 and Shotcrete Gun 260 were leased from Surecrete, Inc., and evaluated at the Tyndall AFB, Florida SKY X test range in September of 1991. Both pieces of equipment performed satisfactorily. Master Builders Technologies did not have Meyco shotcrete equipment available for lease within a timeframe acceptable to the schedule of this development effort. Consequently, no Meyco shotcrete equipment was evaluated in the field.

E. CONCLUSIONS

Based on field evaluation results, an ERSF system to repair damaged and destroyed reinforced concrete walls, and other structural members, using shotcrete and commercially available shotcrete equipment is a viable concept. Such a system, if fielded, would provide a significant improvement in a FOB's ability to repair mission-critical reinforced concrete structures. Such a capability would greatly improve the ability of a FOB to recover after an attack.

F. RECOMMENDATIONS

Full-scale development of a shotcrete-based ERSF system should be undertaken. Upon successful completion of full-scale development, a shotcrete-based ERSF system should be deployed to FOBs to improve BRAAT capability.

PREFACE

This report was prepared by Applied Research Associates, Inc. (ARA), under contract F08635-88-C-0067, for the Air Force Civil Engineering Support Agency (AFCESA), Civil Engineering Laboratory, Tyndall AFB FL.

This report summarizes work done between December 1990 and September 1991. Capt. Richard A. Reid was the AFCESA/RACS Project Officer for the subtask under which this work was accomplished.

This report has been reviewed by the Public Affairs Office, and is releasable to the National Technical Information Services (NTIS). At NTIS, it will be available to the public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of the effort described in this report was to identify, then evaluate in the field, the most promising high output, automated, remotely controlled piece of shotcrete equipment for use in a shotcrete-based Expedient Repair of Structural Facilities (ERSF) system developed by the Air Force Civil Engineering Support Agency's Airbase Survivability Branch (AFCESA/RACS). ERSF systems are used to rapidly repair mission-critical structural facilities on Forward Operating Bases (FOBs) after an attack. Fielding of ERSF systems will improve the ability of a FOB to fulfill its mission after an attack, by enhancing the Base Recovery After Attack (BRAAT) phase of the Airbase Operability (ABO) concept.

A shotcrete-based ERSF system will primarily be used to repair destroyed, damaged, or breached walls in reinforced concrete structures. Additional uses of a shotcrete ERSF system, such as participation in routine civil engineering construction/maintenance activities or the rapid construction of defensive positions during wartime, are left to the discretion of the base commander and/or base civil engineer (BCE).

B. BACKGROUND

In 1985 at Spangdahlem Airbase (AB), Federal Republic of Germany (FRG), the NATO air base survivability exercise SALT Y DEMO dramatically underscored the need for reliable postattack communications and a facility recovery plan. The ABO concept evolved from SALT Y DEMO. Its five phases are defense, survival, recovery, aircraft sortie generation, and sortie support. ERSF systems deal with the recovery, i.e., BRAAT, phase of ABO.

During SALTY DEMO, when Damage Assessment Teams (DATs) in the field informed the Damage Control Center (DCC) of a damaged mission-critical facility, the DCC could give them little to no guidance on how to repair the facility. This highlighted the fact that the Air Force did not have systems in-place at FOBs to expediently repair mission-critical facilities. Without such a capability, the ABO concept, and consequently airbase mission fulfillment, are jeopardized. As a result of this capability shortfall, the ERSF system development effort described in References 1 and 2 was undertaken by AFCESA/RACS.

One of the ERSF systems developed and field tested by AFCESA/RACS uses a dry-mixed, steel fiber-reinforced, rapid-setting, high early-strength shotcrete material to repair destroyed/damaged walls and wall breaches. Development of this shotcrete material by AFCESA/RACS is described in Reference 3. This material achieves a compressive strength of at least 3,500 psi within one hour. To efficiently and flexibly apply this material under a wide range of repair scenarios with a minimum number of personnel, AFCESA/RACS conducted a research effort to identify, and then evaluate in the field, the most promising piece of shotcrete equipment that provides the desired capabilities. That research effort is documented in this report.

C. SCOPE

Following the shotcrete-based ERSF system field test documented in Reference 1, an ERSF Shotcrete Equipment Specification was drafted. This equipment specification is presented in Appendix A. Using this equipment specification as a baseline, shotcrete equipment candidates were identified and screened for use in a shotcrete-based ERSF system, by means of a literature review and phone queries to equipment manufacturers. Based on the literature review and phone queries, the most promising candidate equipment was identified. This piece of equipment was screened further by a field trip to its manufacturer. After completing the screening process, the selected equipment was brought to Tyndall AFB, Florida for an in-depth field evaluation. Based on this field evaluation, recommendations for future full-scale development, leading to the eventual fielding of a shotcrete-based ERSF system were made.

SECTION II

EQUIPMENT SCREENING AND PRELIMINARY EVALUATION

A. THE SHOTCRETE REPAIR PROCESS

In the simplest form of the shotcrete repair process, dry-mix shotcrete (explained below) is sprayed onto a plywood backing placed behind the repair area, using a gun, hoses, and a hand-held spray nozzle. Hoses are required to carry water, compressed air and shotcrete material. The gun consists of a hopper and a revolving cylinder (rotor) under the hopper. The diameter and length of the rotor, along with the number and size of its holes, control the gun's material output.

In the dry-mix shotcrete process, dry shotcrete material is fed into the hopper, and then passes through the holes in the revolving rotor to a hose attached to the gun. Compressed air propels the dry shotcrete material through a hose to a hand-held nozzle at the end. At the nozzle, water is mixed with the shotcrete material and the wet shotcrete is then sprayed onto the backing guided by the nozzle operator. In addition to the equipment just described, all that is needed for the system to work is: (1) a water source of sufficient pressure and flow rate; (2) an electrical source of sufficient voltage and power, having the correct frequency and number of phases; (3) compressed air of sufficient flow rate and pressure; and (4) shotcrete material.

The basic system described above uses a person to control the spray nozzle. In a shotcrete-based ERSF system, a spray nozzle attached to a remotely controlled robotic boom is desirable; it reduces crew fatigue, allows higher material output rates because a person is not providing the reaction force at the nozzle, and makes it possible to cover a much larger area without moving the equipment.

For more detailed descriptions of the shotcrete process, see References 1, 3, and 4.

B. SHOTCRETE EQUIPMENT SCREENING

Thomas Register (1990), Civil Engineering, Engineering News Record, Tunnels & Tunnelling (World Profile of Contractors and Consulting Engineers), and various other similar sources were researched to find major manufacturers of shotcrete equipment in the United States and abroad. It was determined that the number of companies manufacturing shotcrete equipment that may, with minimum development, meet most or all the provisions of the Draft ERSF Shotcrete Equipment Specification is limited (see Table 1).

After contacting each company listed in Table 1, it was determined that equipment manufactured by Aliva Ltd. of Sweden (marketed by Surecrete, Inc. in the U.S.) and Meyco Ltd. of Austria (marketed by Master Builders Technologies in the U.S.) showed the most promise of meeting the system specification. Both these companies specialize in shotcrete equipment for lining tunnels and mines, where automated, remotely-controlled, high output shotcrete equipment is frequently used. Another company, Stabilator AB of Sweden, also manufactures suitable equipment, but no U.S. distributor could be found. This highlights a problem uncovered during this investigation. Sophisticated shotcrete equipment developed to line tunnels and mines is not often used in the U.S. Consequently, few companies market their equipment here. This fact limited the number of manufacturers having equipment suitable for evaluation during this research effort to two: Surecrete, Inc. and Master Builders Technologies.

Surecrete, Inc. and Master Builders Technologies were contacted again to determine whether they had any suitable equipment on hand to be inspected/evaluated by a field trip to each manufacturer. Master Builders stated they had no suitable equipment on hand, nor would they have any for 3 to 4 months. Unfortunately, such a long delay could not be tolerated; consequently, evaluation of equipment from Master Builders was not pursued further.

When contacted, Surecrete, Inc. indicated they had several high-output, remotely controlled, robotic boom-based pieces of shotcrete equipment on hand at a manufacturing site located in Vancouver, British Columbia (BC). AFCESA/RACS sent the author to the site to inspect the equipment and conduct a preliminary evaluation.

C. PRELIMINARY EQUIPMENT EVALUATION

On 15 April 1991, the author traveled to Surecrete, Inc. to do a preliminary evaluation of two remotely controlled, robotic shotcrete boom/nozzles. These pieces of equipment were candidates for use in a shotcrete-based ERSF system.

1. Candidate Equipment

The following discussions of shotcrete equipment deal with the remotely-controlled, robotic spray boom/nozzle portion of the shotcrete system. This is the most critical part of a successful ERSF shotcrete system. The shotcrete gun, so long as it provides sufficient material output, is not the critical portion of a shotcrete-based ERSF system.

a. Equipment-1 (Aliva Spray Boom 305.3)

The first piece of equipment, shown in Figure 1, is self-propelled, and the entire platform on which the automated spray boom rests can be raised to increase its reach. The spray boom, used to apply the shotcrete, is controlled by a remote, portable control panel, shown in Figure 2. Table 2 summarizes the spray boom major specifications. The maximum forward speed of the equipment is approximately 30 mph, while the platform on which the boom rests can be raised to a maximum height of 15 feet. This equipment was used during an on-site demonstration, in which a 4-foot high, 8-foot wide, 8-inch deep plywood section, placed on a platform 20 feet off the ground, was filled with shotcrete (see Subsection II-D.).

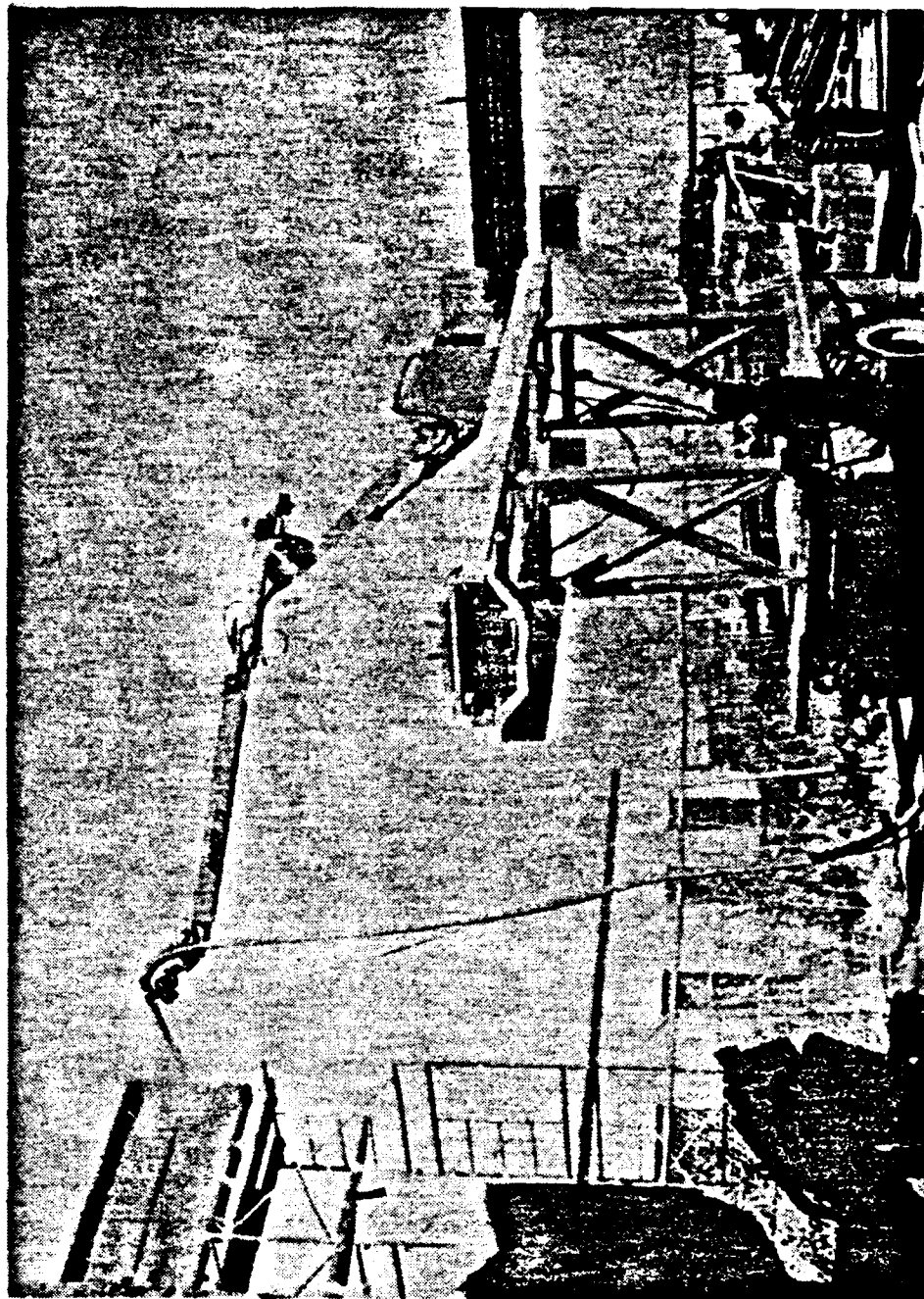


Figure 1. Aliva Spray Boom 305.3 Equipment (Equipment-1).

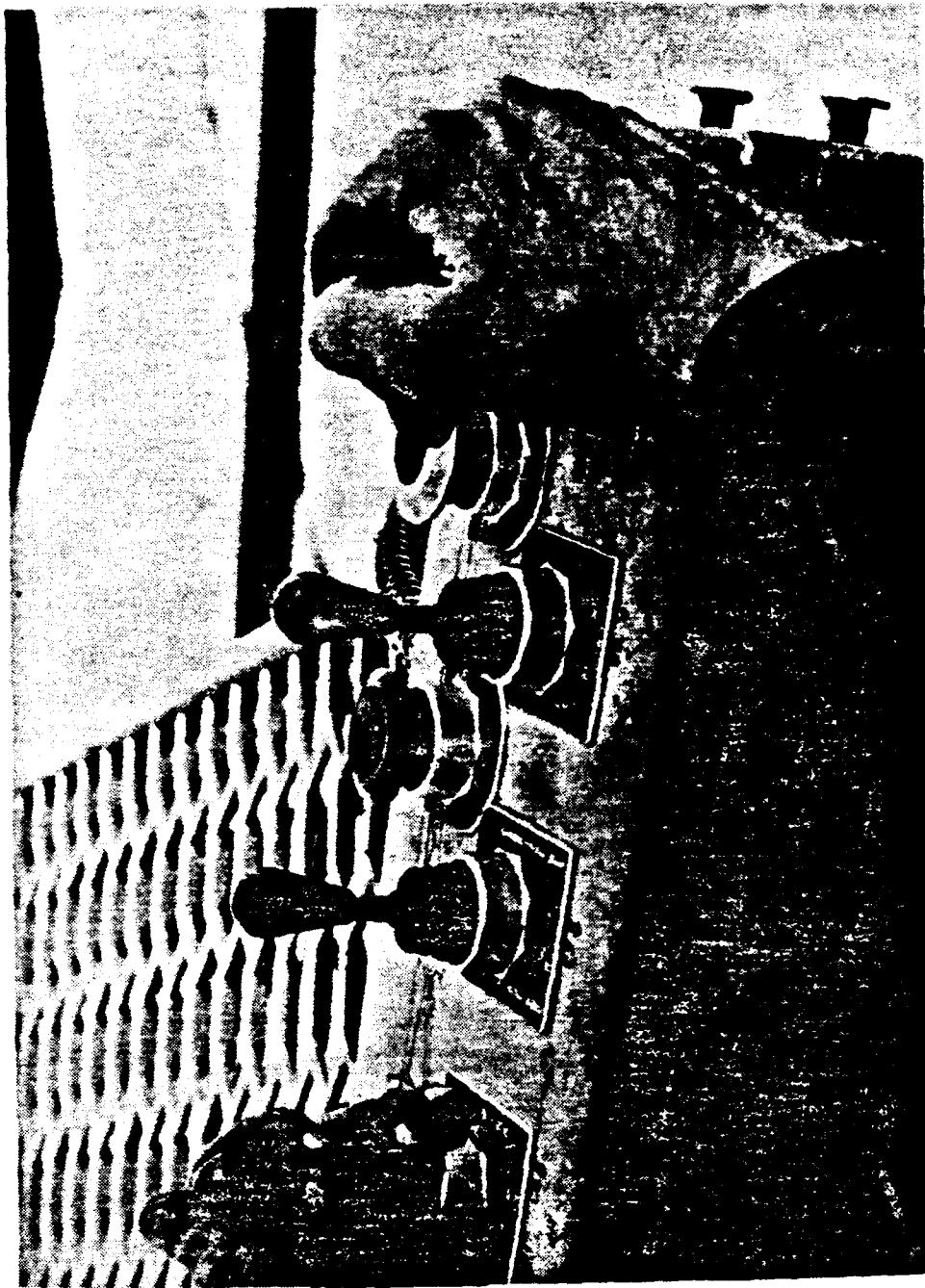


Figure 2. Control Panel For Aliva Spray Boom 305.3 Equipment.

TABLE 1. ALIVA SPRAY BOOM 305.3 MAJOR SPECIFICATIONS.

Power Source	Pneumatic Motor
Max. Height	20.44 feet + 15 feet*
Min. Height	1.80 feet
Max. Reach	50.85 feet
Min. Reach	13.45 feet
Weight	3,660.3 lbs + 5267.00 lbs**
Cost on 4/15/91 (Approx.)	\$45,000.00 + \$32,000.00***

* - Add 15 feet when chassis platform of vehicle is fully extended.

** - Weight of boom plus vehicle.

*** - Cost of boom plus vehicle (estimated).

b. Equipment-2 (Aliva Spray Boom 80)

The second piece of equipment, shown in Figure 3, is not self-propelled, but is carried on the forks of a large forklift (5,000-pound capacity or greater). This equipment also uses a remotely controlled, robotic spray boom to apply shotcrete. The boom is controlled by a control panel similar to the one shown in Figure 2. Table 3 summarizes this spray booms major specifications.

2. Equipment Demonstration

On 16 April 1991, a demonstration of Equipment-1 (Spray Boom 305.3) was conducted at the Vancouver, BC manufacturing site. An 8-foot wide, 4-foot high, 8-inch deep plywood section, placed on a platform 20 feet off the ground, was filled with shotcrete using a remote, handheld toggle switch panel to control the spray boom. This process is shown in Figures 4 and 5. It took 14 minutes and 27 seconds to fill the plywood section. The shotcrete gun used during the demonstration had a maximum material output rate of approximately 3 to 4 cubic yards per hour. The gun is shown in Figure 6.

While Equipment-1 showed good performance and flexibility during the demonstration, Equipment-2 (Spray Boom 80) was selected for the field demonstration at Tyndall AFB, Florida. This decision was made for several reasons. First, the purchase or lease costs for the Spray Boom 80 equipment were much less than for the Spray Boom 305.3 equipment. Second, the Spray Boom 80 is less complex, smaller, and, if attached to an all-terrain forklift, more maneuverable. Each of these advantages is a critical factor for ERSF equipment. The less complex a piece of equipment, the easier it is to train personnel on its use and maintenance. The smaller and more maneuverable a piece of equipment, the more easily it can access repair areas in the typically crowded conditions at a FOB. Finally, the Spray Boom 80 equipment provides the same material output rate as does the Spray Boom 305.3, but with a smaller and lighter equipment package, so long as the same size shotcrete gun is used for both. The only disadvantage of Spray Boom 80 is that its reach is less than that of the Spray Boom 305.3 mounted on Equipment-2 (see

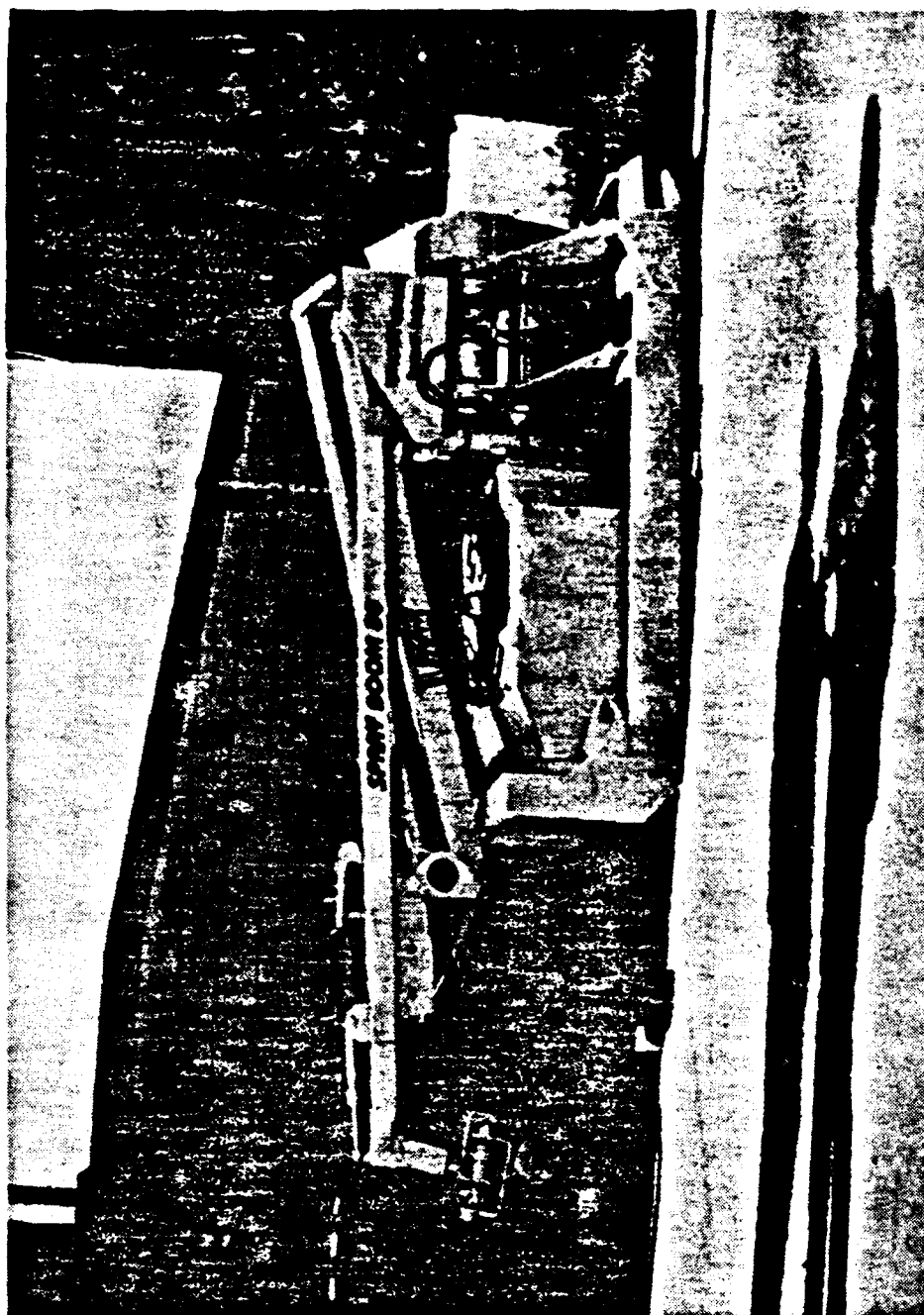


Figure 3. Aliva Spray Boom 80 Equipment (Equipment-2).

TABLE 2. ALIVA SPRAY BOOM 80 MAJOR SPECIFICATIONS.

Power Source	Pneumatic Motor
Max. Height	12.32 feet*
Min. Height	1.00 feet
Max. Reach	15.50 feet
Min. Reach	4.45 feet
Weight	3,860.0 lbs**
Cost on 4/15/91 (Approx.)	\$60,000.00***

*** - Does not include lift height of forklift carrying the boom.**

**** - Weight of boom without forklift.**

***** - Cost of boom only (estimated).**



Figure 4. View 1 of Vancouver BC Equipment Demonstration.

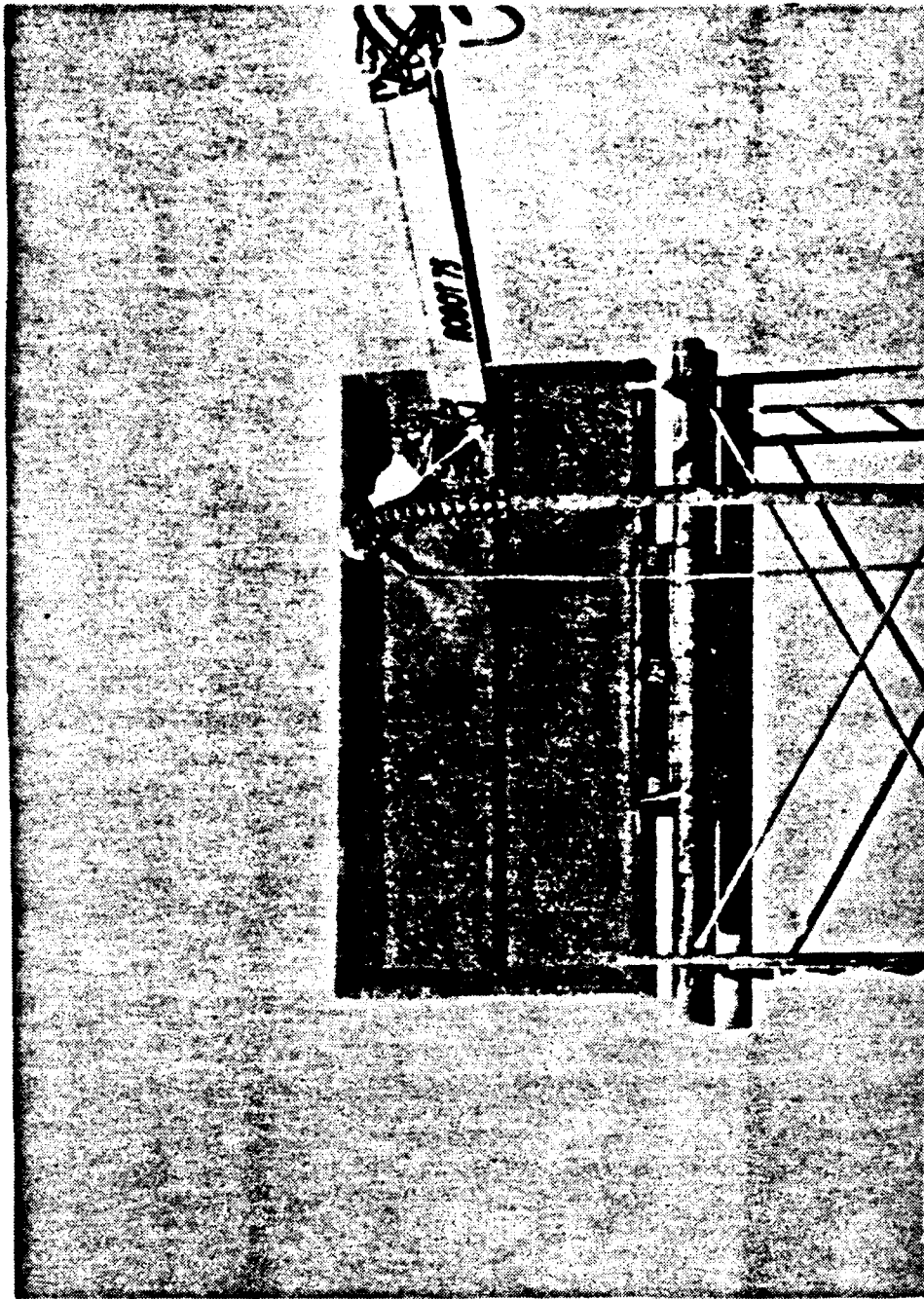


Figure 5. View 2 of Vancouver BC Equipment Demonstration.

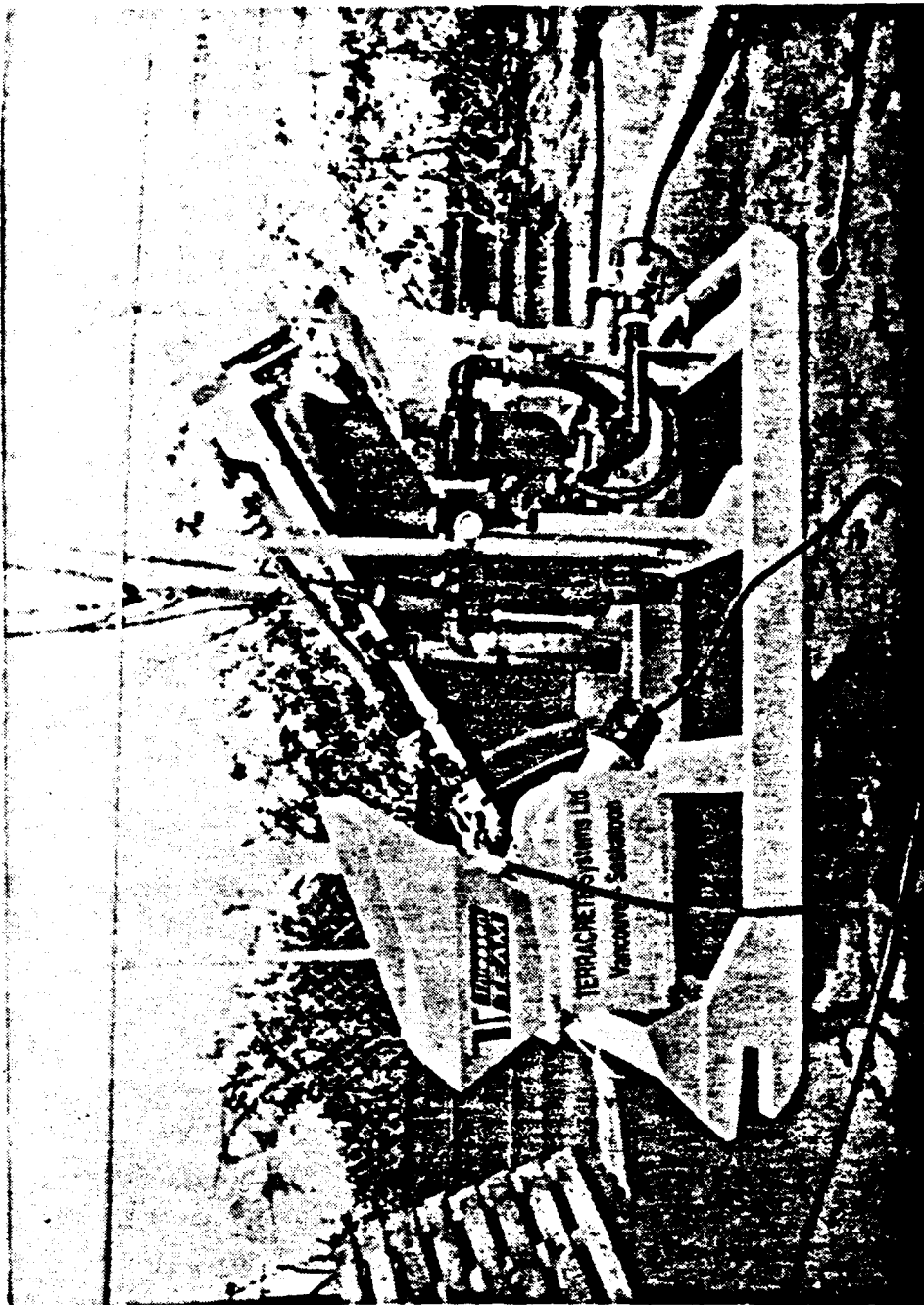


Figure 6. Shotcrete Gun Used For Vancouver BC Equipment Demonstration.

Tables 2 and 3). However, this disadvantage is offset by the fact that it can be maneuvered in areas around structures that the Spray Boom 304.3 cannot reach.

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SECTION III

FIELD EVALUATION AT TYNDALL AFB

A. OVERVIEW

1. Equipment

As already explained, the Aliva Spray Boom 80 was selected for field evaluation at Tyndall AFB. An Aliva 260 shotcrete gun was selected to pump the dry shotcrete material to the boom. This gun is shown in Figure 7. Technical data on the Aliva 260 shotcrete gun is presented in Table 4. This gun provides a maximum material output rate of approximately 8 to 12 cubic yards per hour.

Both pieces of equipment mentioned above, along with necessary hoses, nozzles, and spare parts, were leased from Surecrete, Inc., for 2 months, using an Air Force Form-9. The cost of the lease was \$9,500.00 per month. The purchase price of the equipment is approximately \$95,000.00. In addition to the equipment, two Surecrete technical advisors (Mr. Fred Sherrill and Mr. Andrew Smith) came to Tyndall with the equipment to train AFCESA/RACS personnel on the use and maintenance of the equipment. The cost of their services was 325.00/each per day, for 5 days.

The equipment was leased for 2 months so it could also be used in the Expedient Repair of Structural Facilities (ERSF) and Postattack Damage Assessment (POSTDAM) Tyndall AFB Field Demonstration, scheduled to take place immediately after the Shotcrete Equipment Field Evaluation. The ERSF and POSTDAM Tyndall AFB Field Demonstration is described in Reference 5.

Equipment provided by the Air Force for the evaluation consisted of an air compressor providing 600 cubic feet per minute (CFM) at 125 psi, a 60-kilowatt (KW) generator set providing 480 volt/three-phase/60 cycle power, and a water source. Initially, a 55-gallon drum with a drum pump, fed by tap water, then direct connection to the local water system were tried as the

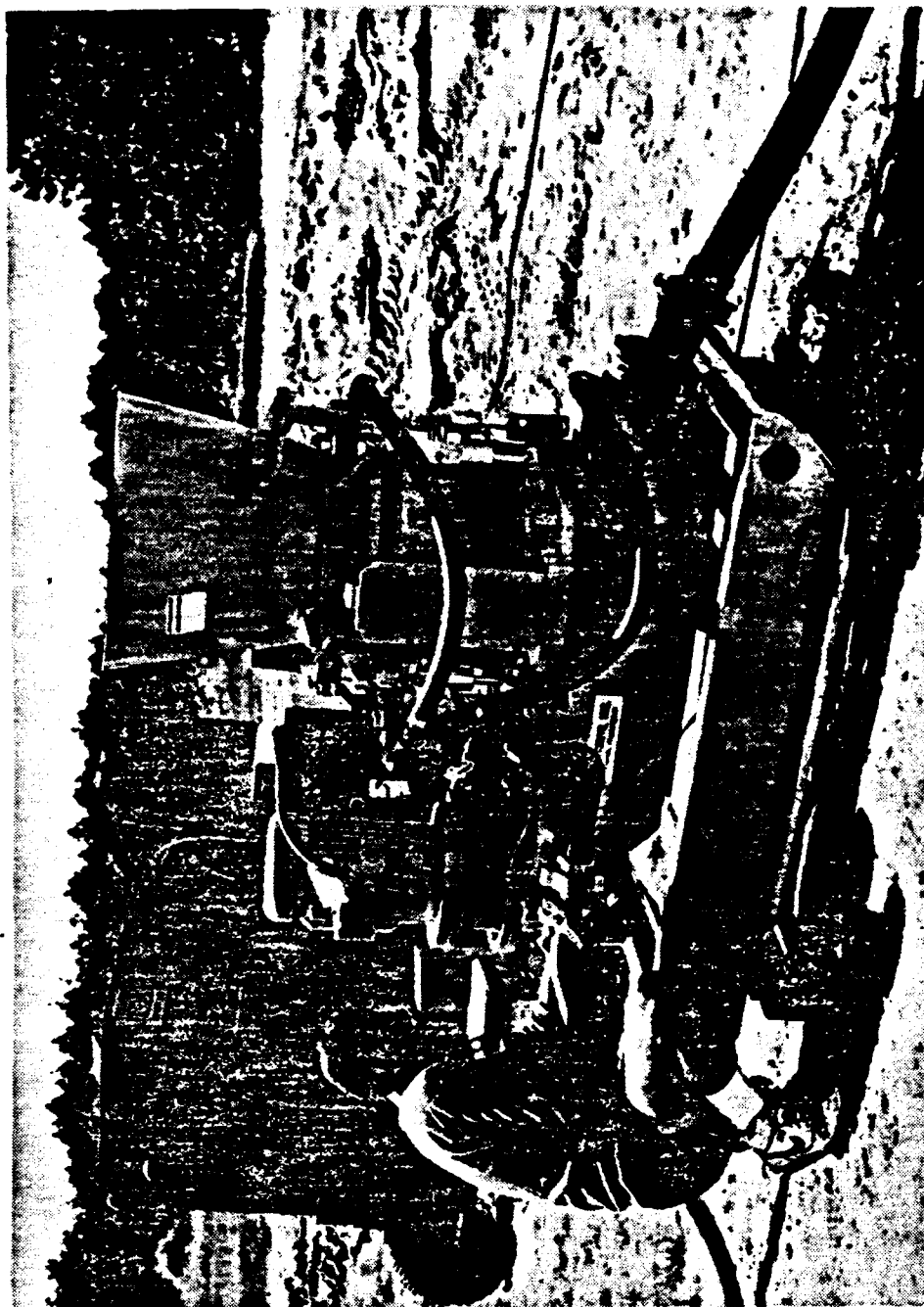


Figure 7. Aliva 260 Shotcrete Gun Used For Tyndall AFB Field Demonstration.

TABLE 3. ALIVA 260 SHOTCRETE GUN SPECIFICATIONS.

Power Source	Electric Motor IEC three-phase 600 Volt, 60 Hz 7.5 kW @ 1460 rpm 5.5 kW @ 950 rpm
Compressed Air Source	353 to 670 CFM @ 100 PSI
Water Source	10 GPM @ 90 PSI
Cylinder (Rotor) Capacity	0.56 ft³
Hose Diameter	2.56 to 3.35 inches
Conveying Line Diameter	2.56 to 2.95 inches
Material Output Capacity	7.85 to 11.77 yd³/hour
Aggregate Size normal/max.	0.63 inches / 0.98 inches
Conveying Distance	
Horizontal	985 feet
Vertical	328 feet
Cost on 4/15/91 (Approx.)	\$35,000.00

water source, but these methods did not provide the required flow rate and pressure. Finally, a large water truck was used (see subsection III-B.)

2. Shotcrete Material

It was originally intended to use the AFCESA/RACS developed shotcrete material described in Reference 3 for the Tyndall AFB field demonstration. However, waiting for the material to be delivered would have delayed the demonstration from 4 to 6 weeks. This long delay was unacceptable. Consequently, a rapid-setting, high-strength, steel-fiber-reinforced shotcrete material manufactured by Surecrete, Inc. was substituted. This material flash-sets like the AFCESA/RACS material, but does not attain the 3,500 psi or greater compressive strength within 1 hour. This lack of strength was not a factor during the evaluation, because no explosive testing of the repair was to be done immediately, due to the lack of an approved environmental impact statement for the explosive testing at the Tyndall AFB SKY X range. Additionally, the spraying characteristics of the two materials are very similar, so using the Surecrete, Inc., material did not affect the outcome of the evaluation.

Six cubic yards of the Surecrete, Inc., shotcrete material were obtained, for both the field evaluation and the subsequent ERSF and POSTDAM Field Demonstration. The cost of the material was \$300.00 per cubic yard. The material was bagged in supersacks, which are double-lined plastic bags containing 1 cubic yard of material. Lifting straps are attached to the top of the bag, and a drawstring funnel, through which the material flows into the hopper of the shotcrete gun, is located at the bottom of the bag. The funnel can be opened and closed to control the material flow rate. A supersack of material suspended over the Aliva 260 shotcrete gun hopper is shown in Figure 8.

3. Evaluation Location

The field evaluation was conducted at the Tyndall AFB SKY X test ranged. The NATO test structure at this range was used for the evaluation. Two openings in the east wall of the structure were backed with plywood.

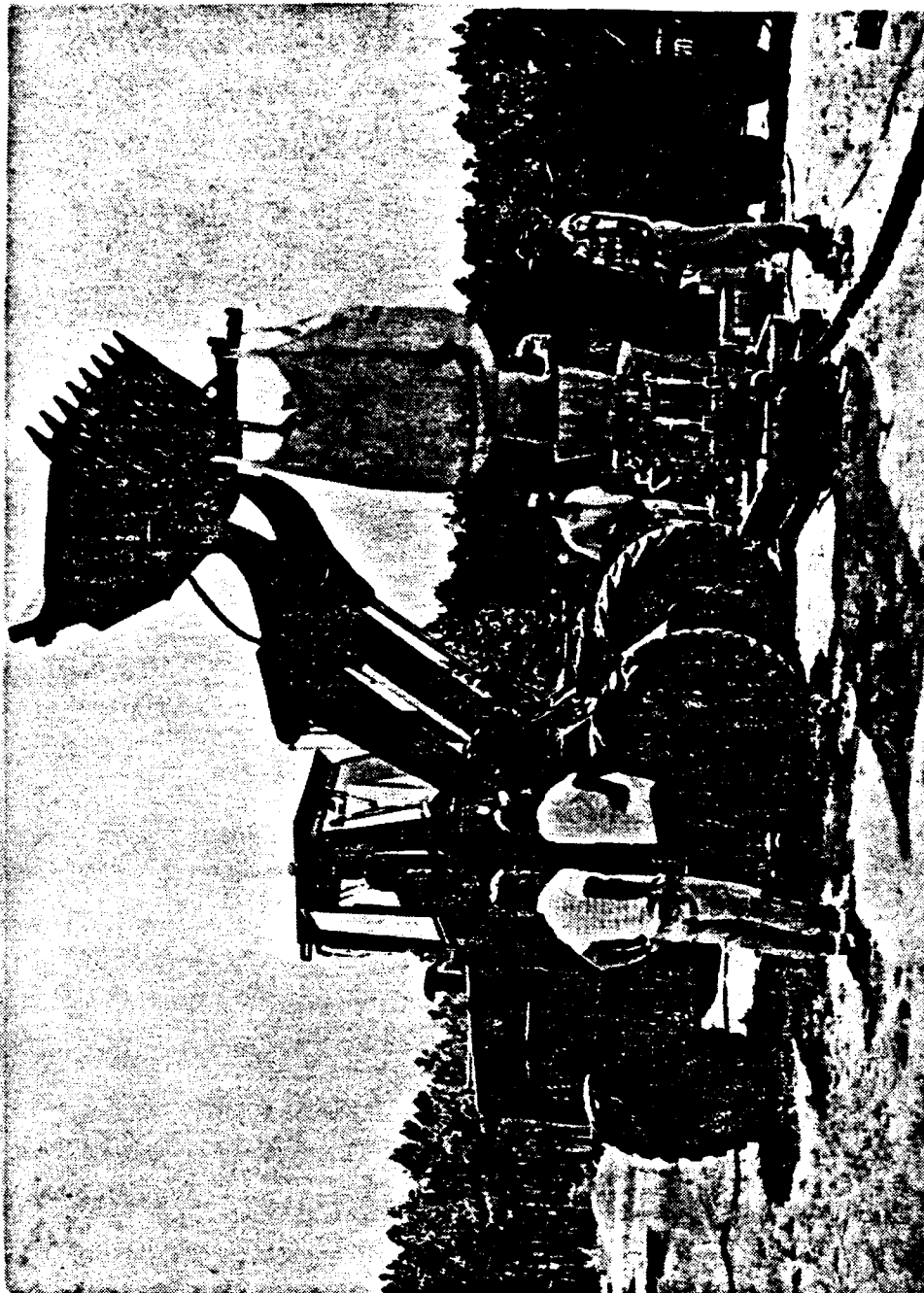


Figure 8. Supersack Suspended Over The Allva 260 Shotcrete Gun Hopper.

These openings are shown in Figure 9. The lower opening is a doorway that was filled in with the AFCESA/RACS shotcrete material during a previous test (see Reference 3). During subsequent explosive testing, a hole approximately 5 feet in diameter was punched through the shotcrete, behind which the plywood backing was placed. The upper opening, which is directly above the door, is in the penthouse of the NATO structure. This opening is 7 feet high by 5 feet, 1 inch wide. Both plywood backings were placed in the openings to allow a repair thickness of 10 inches.

B. EQUIPMENT EVALUATION

1. Description

The shotcrete equipment and material arrived at the Tyndall AFB 9700 area on the afternoon of 25 September 1991. The equipment was assembled and checked out that afternoon and evening. The first step on the morning of 26 September was to begin training the boom/nozzle operator. Initial training was conducted at the 9700 area, and consisted of general instruction followed by the trainee (Mr. Norm Karaszewski of Applied Research Associates) manipulating the boom/nozzle using the remote control panel. Use of the control panel is shown in Figure 10. This portion of the training lasted approximately 3 hours.

The equipment was then transported to the SKY X test range on the afternoon of 26 September. The equipment, consisting of the automated boom/nozzle (Aliva Spray Boom 80), shotcrete gun (Aliva 260), generator set, air compressor, water drum and pump, connecting hoses, and a 480/600 volt transformer, were set up and connected (see Figure 11). A flowmeter and control valve were placed in line between the water source and spray boom, so the shotcrete water content could be controlled during the evaluation. The spray boom was mounted on an all-terrain forklift, as shown in Figure 12. Boom operator training at SKY X consisted of manipulating the nozzle, using the control panel, while spraying water from the nozzle, as shown in Figure 13. This portion of the training lasted approximately 1 1/2 hours.



Figure 9. Wall Openings Backed With Plywood In NATO Structure.



Figure 10. Control Panel For Aliva Spray Boom At Tyndall AFB.

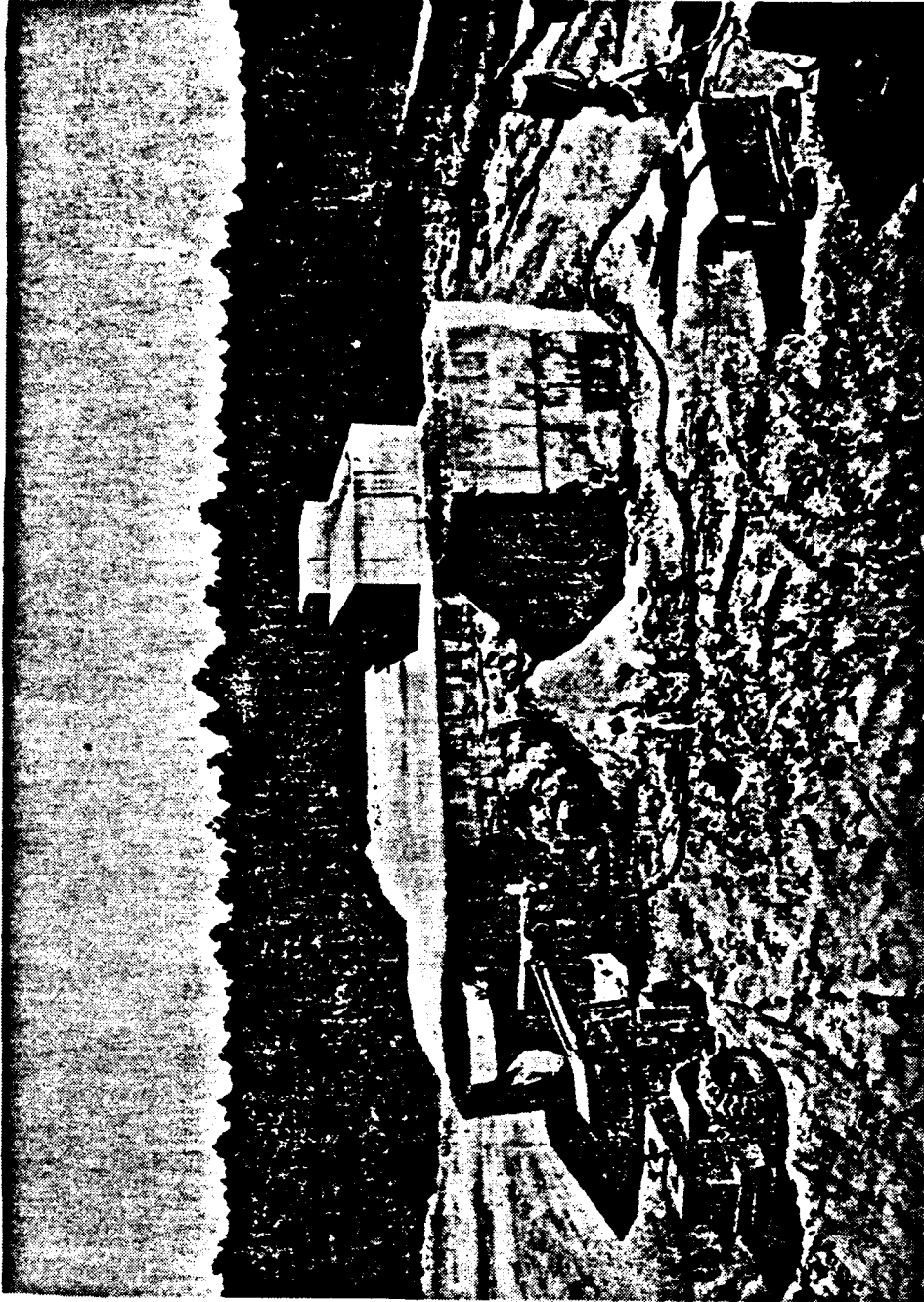


Figure 11. Shotcrete Equipment Setup At Tyndall AFB.



Figure 12. Aliva Spray Boom 80 Mounted On An All-Terrain Forklift.



Figure 13. Spraying Water From Boom/Nozzle During Boom Operator Training.

The shotcrete equipment evaluation began during the late afternoon (approximately 1400) of 26 September. One of the Surecrete, Inc. technical advisors (Mr. Andrew Smith) controlled the water flow rate, and hence the water content of the shotcrete material, during the evaluation. Mr. Fred Sherrill of Surecrete, Inc. controlled the shotcrete gun. The penthouse opening was used for the evaluation.

Shotcrete material was sprayed from the boom/nozzle as shown in Figure 14. However, the initial water source, which was a 55-gallon drum with a drum pump, did not supply water at a sufficient flow rate and pressure to the nozzle. The inline flow meter indicated a maximum flow rate of only 2 gpm, instead of the required 10 gpm. Consequently, the shotcrete was too dry, and did not stick to the plywood backing. Spraying was stopped after approximately 20 minutes, at which point one-and-a-half supersacks of material had been used. Next, the local water system was tried as a water source, and spraying was resumed. However, the local water supply provided only a maximum flow rate of 4 gpm. Spraying was stopped again after approximately 10 minutes, after the other half of the open supersack had been used. Finally, a large water truck with a diesel-powered water pump was located. However, by this time it was late in the day, so it was decided to wait until the next morning (27 September) to continue the evaluation, using the water truck.

The evaluation was resumed beginning at 0800 on 27 September. The water truck easily provided a sufficient flow of water, with the flow varying between 5 and 10 gpm as controlled by Mr. Smith. Shotcrete material rapidly built up on the plywood backing. To conserve shotcrete material for the ERSF and POSTDAM Field Demonstration, spraying was stopped after 15 minutes, when one additional shotcrete supersack had been used.

2. Observations and Conclusions

Once an adequate water supply had been found, the shotcrete equipment performed well. With the correct water flow, material rapidly built up on the plywood backing. Training to manipulate the robotic spray

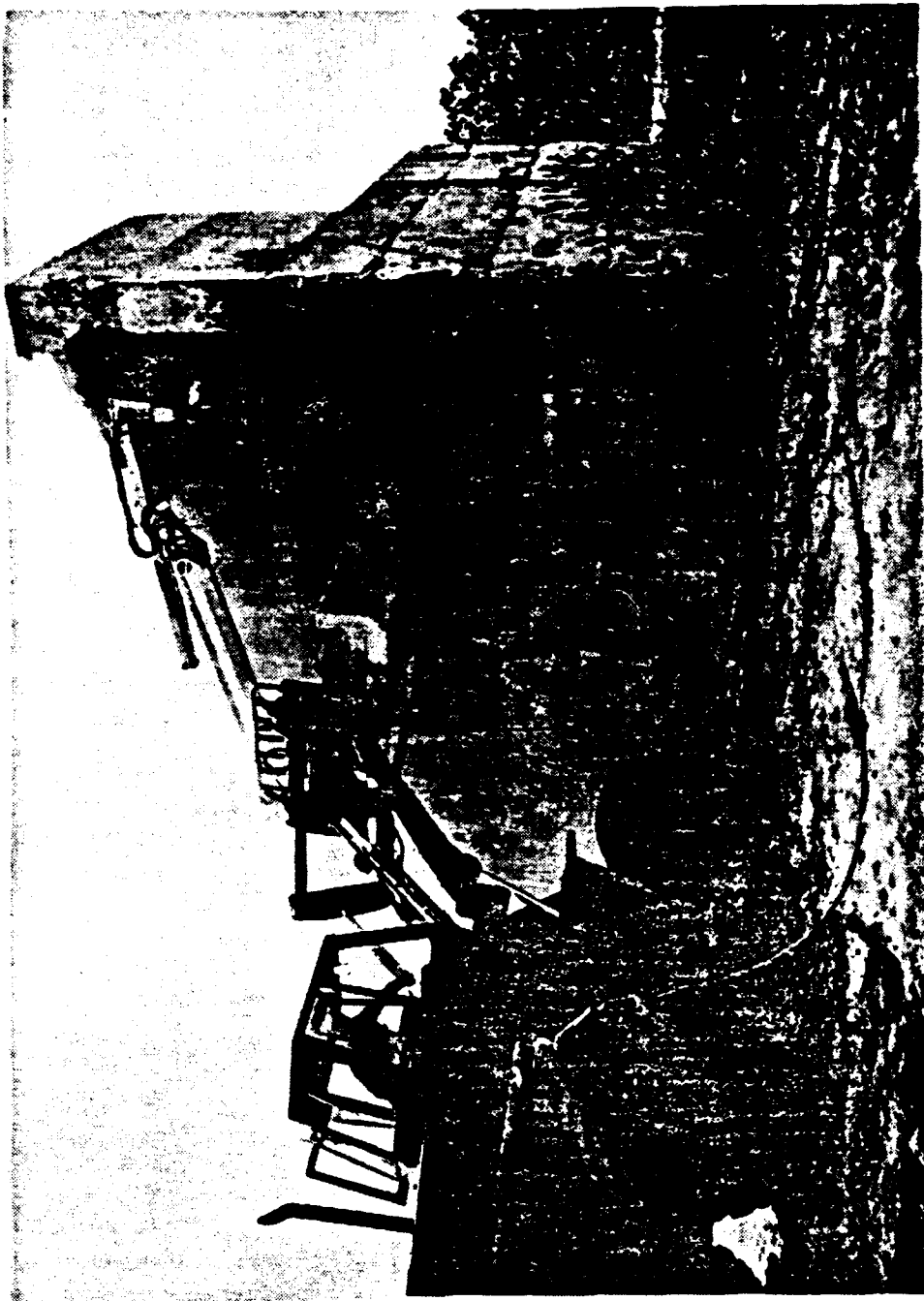


Figure 14. Spraying Shotcrete From Boom/Nozzle During Equipment Evaluation.

boom/nozzle, using the remote panel, is relatively simple and can be accomplished within 1 to 2 days. Training to use the shotcrete gun can be accomplished in several hours. Routine and preventive maintenance were easy to accomplish. No major maintenance problems were encountered during the evaluation. The supersacks greatly eased the task of keeping the shotcrete gun hopper filled. Additionally, the supersacks provide a convenient way of storing the shotcrete material in a waterproof container.

The only significant difficulty in using the equipment is controlling the water content of the shotcrete material. The shotcrete material is very sensitive to water content. Too little or too much water causes the material to not stick to the backing surface. During the evaluation, the best results were obtained when the water flow rate was between 6 and 7 gpm, as indicated by the flowmeter. Visual observation of how the material was sticking to the surface of the repair was used to determine when the flow rate was too low or too high, and to adjust it.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

An ERSF system to repair damaged and destroyed reinforced concrete walls and other structural members, based on shotcrete and commercially available shotcrete equipment, is a viable concept. This conclusion is reinforced by the excellent performance of the shotcrete equipment discussed here during both the ERSF and POSTDAM Tyndall AFB Field Demonstration, and the U.S. Air Force FOAL EAGLE airbase ground defense exercise at Osan AB, Korea. Results from the demonstration and exercise are discussed in Reference 5.

The number of manufacturers producing automated, high-output shotcrete equipment is limited. Present use of such equipment is mainly confined to the mining and tunneling industries. The research effort reported herein showed that such commercially available equipment is suitable for ERSF. The evaluation results showed that the equipment is easy to use and maintain, but control of the shotcrete water content is critical. Additionally, evaluation results, along with results described in Reference 5, indicate that the separate components of the shotcrete system (robotic boom, gun, shotcrete storage to feed the gun hopper, air compressor, generator, and water source) should be integrated into a single unit. At least, the gun, boom, and water source should be integrated together. The generator and air compressor could be provided from existing FOB resources. The integrated unit should be as small as possible, so the maneuverability and agility of the equipment will be adequate to access likely repair areas at FOBs. A self-contained unit will eliminate setup problems, and simplify equipment use. The unit would be largely self-supporting, requiring only water, shotcrete material, and fuel to function. By minimizing the equipment's dependence on external FOB BRAAT resources, the equipment availability and supportability in a postattack environment would be enhanced.

The shotcrete equipment evaluated during this effort does not fully meet the Draft Shotcrete Equipment Specification contained in Appendix A. However, with further development to meet the goals outlined in the preceding paragraph, a shotcrete-based ERSF system should be able to satisfy most, if not all, of the system specification provisions.

Finally, an ERSF shotcrete system would provide a significant improvement in a FOB's ability to repair mission-critical reinforced concrete structures. Such a capability would significantly improve the base's ability to recover from an attack.

B. RECOMMENDATIONS

Full-scale development of a shotcrete-based ERSF system should be undertaken. Development should use the Draft Shotcrete Equipment System Specification as a guide. An integrated system, in which the robotic spray boom, gun, generator, air compressor, water source, and shotcrete material storage are contained in a single unit, is the desired configuration, so long as size can be kept within acceptable limits. The ability to heat water to at least 70 degrees Fahrenheit before mixing with the shotcrete material should be provided. Upon successful completion of full-scale development, a shotcrete-based ERSF system should be deployed to FOBs to improve BRAAT capability.

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APPENDIX A

**EXPEDIENT REPAIR OF STRUCTURAL FACILITIES (ERSF)
SHOTCRETE EQUIPMENT SPECIFICATION
(DRAFT)**

11 April 1991

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A. INTRODUCTION

The Air Force Civil Engineering Support Agency's Airbase Survivability Branch (AFCESA/RDCS) is developing systems to expediently repair mission-critical structural facilities in a postattack environment at forward operating bases (FOBs). One of the Expedient Repair of Structural Facilities (ERSF) systems being developed uses a dry-mix, steel fiber reinforced, rapid setting, high strength shotcrete material to repair breached walls and other types of conventional weapon damage to reinforced concrete structures. The shotcrete material used in this system was developed by AFCESA/RACS during the spring and summer of 1990. An ERSF system using this material was demonstrated in the field at Tyndall AFB, Florida, in late October 1990. Results from the demonstration showed that the shotcrete material was suitable for ERSF, but the long-term storage requirements of the material needed investigation. Additionally, the demonstration showed that shotcrete equipment suitable for ERSF, with respect to such factors as material placement rates, material placement flexibility, equipment mobility, material/water storage requirements, equipment simplicity and maintenance, and personnel requirements, needed to be identified and evaluated.

This paper, which is a draft ERSF Shotcrete Equipment Specification, is the first step in the equipment identification and evaluation process described above. This specification will be the basis for the identification and subsequent evaluation of shotcrete equipment suitable for ERSF. Identified shotcrete equipment will be evaluated through a field demonstration, where it will be used to repair an explosively formed breach in a reinforced concrete wall under realistic conditions.

B. ENVIRONMENTAL OPERATING REQUIREMENTS

ERSF shotcrete equipment must be able to carry out repair operations under the following environmental conditions.

1. Ambient Temperature

ERSF shotcrete equipment must be able to operate in an ambient thermal temperature range of 15 to 100 degrees Fahrenheit.

2. Material Temperatures

ERSF shotcrete equipment must be able to operate when the temperature of the shotcrete material is between 40 and 90 degrees Fahrenheit. When necessary, the shotcrete equipment must be able to heat the water required by the shotcrete material to a minimum of 70 degrees Fahrenheit (see Section C-2). Consequently, no water temperature range requirement is given in this specification.

3. Precipitation

The ERSF shotcrete equipment must be usable in a rainstorm of 1-inch per hour intensity, or in the equivalent amount of snowfall (approximately 7 inches per hour), hail, sleet, and/or freezing rain.

4. Light

The ERSF shotcrete equipment must be usable day and night, and in foggy or in smokey conditions with visibility less than 50 feet.

5. Chemical/Biological Agents

The ERSF shotcrete equipment must be usable in the presence of chemical and biological agents, with personnel operating the equipment in full chemical gear ensemble. ERSF systems are not designed for a nuclear environment.

C. EQUIPMENT CAPACITIES AND PERFORMANCE REQUIREMENTS

The ERSF shotcrete equipment capacities and performance requirements presented here are based on the following information and assumptions.

- The shotcrete equipment must be able to repair five, 5-foot diameter, 12-inch thick wall breaches (volume = 0.73 cubic-yards per breach) without requiring refilling with shotcrete material or water.

- Shotcret material wastage from rebound and other causes is 0.6 cubic-feet fpr every 1.0 cubic-feet in place.

- The water to shotcrete material ratio is 8.555-percent by weight.

- The weight of the shotcrete material without water is 121 pounds per cubic foot.

- The shotcrete material is packaged in supersacks. Supersacks are large capacity (approximately 2,500 pounds of material), plastic lined bags that can be lifted by a hoist, crane, or other piece of heavy equipment. A supersack has a funnel at its bottom, through which shotcrete material can be fed into the equipment's storage tanks.

- The bagged shotcrete material contains all necessary aggregate, additives, and steel fibers. Once placed in the equipment, only water must be added to the material during the repair process.

- After backing the breach with plywood, and installing conventional steel reinforcement (if used), the equipment must be capable of filling the breached area with shotcrete material to a thickness of 12 inches within 5 minutes.

- The shotcrete equipment must have a remotely operated, hydraulic spraying arm with an attached shotcrete nozzle for most repair applications.

- Repairs can occur up to 300 feet away from the nearest location at which the shotcrete equipment can be positioned. For this type of repair, a standard hose/nozzle arrangement must be used to apply the material to the repair area.

- Repairs can occur on the second story of a structure, with a maximum vertical elevation of 20 feet above the shotcrete gun

1. Shotcrete Material Storage

Based on the five, 5-foot diameter, 12-inch thick wall breach repairs already mentioned, the ERSF shotcrete equipment must be able to store:

$$(0.73 \text{ yd}^3/\text{breach}) \times (5 \text{ breaches}) \times (1.6 \text{ material wastage factor}) \\ = 5.82 \text{ cubic yards of shotcrete material } \underline{\text{(use 6 cubic yards)}}.$$

The material can be stored on-board the equipment or in a towable container. If a towable container is used, it must be possible to feed the material directly from the container into the shotcrete gun.

2. Water Storage

Assuming a safety factor of 1.5 for system flushing and other contingencies, the required on-board or towable water storage for the equipment is:

$$(6 \text{ yd}^3 \text{ of material}) \times (121 \text{ pounds of material/ft}^3) \times (27 \text{ ft}^3/\text{yd}^3) \\ = 19,602 \text{ pounds of shotcrete material}$$

/and/

$$(19,602 \text{ pounds}) \times (8.555\text{-percent water/material ratio}) \\ = 1,677 \text{ pounds of water}$$

/thus/

$$((1,677 \text{ pounds of water}) / (62.4 \text{ pounds/ft}^3)) \times (7.481 \text{ gal/ft}^3) \\ \times (1.5 \text{ safety factor}) = 302 \text{ gallons of water } \underline{\text{(use 325 gallons)}}.$$

The shotcrete equipment must have an on-board, thermostatically controlled water heater. The heater must be able to heat the 325 gallons of water from a temperature of 40 degrees Fahrenheit to 70 degrees Fahrenheit within one hour, at an ambient air temperature of 15 degrees Fahrenheit.

3. Material Output Capacity

To accomplish a breach repair of the sepcified size in 5 minutes, the minimum required material application rate of the shotcrete equipment is:

$$(0.73 \text{ yd}^3/\text{breach}) \times (\text{breach}/5 \text{ minutes}) \times (60 \text{ minutes}/\text{hour}) \times \\ (1.6 \text{ material wastage factor}) = 14.01 \text{ cubic yards per hour} \\ \text{(use 14.0 cubic yards per hour).}$$

This material application rate is assumed to occur in the horizontal direction.

4. Material Conveying Distance

The horizontal material conveying distance capability through a standard hose/nozzle arrangement must be at least 300 feet. The vertical material conveying distance capability through a standard hose/nozzle arrangement must be at least 50 feet.

5. Hydraulic Spraying Arm

Assuming a 5-foot spraying distance from the tip of the nozzle to the repair area, the hydraulic spraying arm of the shotcrete equipment must meet the following requirements. The distances given are referenced from the front of the equipment along its longitudinal centerline.

- The maximum horizontal reach of the arm must be at least 35 feet.
- The minimum horizontal reach of the arm must be at most 14 feet.

- The maximum vertical reach of the arm must be at least 18 feet.
- The minimum vertical reach of the arm must be at most 2 feet.
- The arm's left/right traverse must be at least +/- 30 degrees.

The arm must be remotely controllable by a single person using a portable, hand held control panel.

6. Equipment Speed

The shotcrete equipment must be self-propelled on pneumatic tires by either a gasoline or diesel engine. The pneumatic tires must be capable of being hardened by a tire filling compound. With hardened tires, the top forward speed of the equipment must be at least 35 miles per hour. The top reverse speed of the equipment must be at least 5 miles per hour.

7. Equipment Range

The shotcrete equipment must have a range of at least 200 miles before requiring refueling.

8. Personnel Requirements

A maximum of two persons must be required to operate the equipment, and both must be carried in the equipment while traveling. This personnel requirement also includes filling the equipment with shotcrete material and water.

9. Lighting

In addition to standard headlights used for traveling during nighttime or inclement weather, the equipment must have attached spotlights, or similar lighting, to illuminate a 50-foot diameter work area around the equipment.

10. Miscellaneous

The equipment must have standard safety features, such as a horn, backup warning beeper, windshield wipers, interior lights, and turn signals. Additionally, to ease maintenance requirements, the equipment shall be constructed from at least 90-percent standard off-the-shelf heavy equipment components, such as the engine, transmission, axles, brakes, and hydraulics.

D. ENVIRONMENTAL STORAGE REQUIREMENTS

Under the storage conditions described below, ERSF shotcrete equipment components must have a service life of 15 years with only routine preventive maintenance. The equipment will be stored in an environment with uncontrolled humidity and temperature.

Preventive maintenance will consist of such things as general cleaning, fluid top-off or replacement, and inspection; and if necessary replacement of seals, hoses, gaskets, and similar items. The minimum time between routine maintenance actions is 6 months.

1. Ambient Temperature

All shotcrete equipment components must be storable in an ambient thermal temperature environment ranging between of -10 and 120 degrees Fahrenheit.

2. Precipitation

Equipment components must not be degraded/damaged by prolonged exposure to rain, snow, sunlight, or other normal climatic elements. If desirable, equipment components can be covered with a tarp or other protective covering to minimize exposure to the elements.

E. SYSTEM RELIABILITY AND MAINTAINABILITY

1. Reliability

All equipment components must be 90-percent reliable throughout their 15 year life-cycle.

2. Maintainability

Required preventive maintenance and repair actions must be accomplished with standard heavy equipment mechanical tools and facilities. Eighty percent of maintenance/repair must consist of standard tasks, such as fluid replacement (oil, hydraulic fluid, brake fluid, etc.), component replacement (alternator, battery, etc.), and engine tune-up and overhaul. Only 20-percent of required maintenance/repair actions can be related to the specialized nature of the equipment. The shotcrete equipment cannot require any specialized maintenance/repair facilities.

F. OTHER SYSTEM REQUIREMENTS

Other shotcrete equipment requirements, such as its interfaces with other Air Base Operability (ABO) systems, are discussed below.

1. Manpower

ERSF systems must operate within the "R" set manpower requirements for ABO. The maximum size of a general ERSF team is four personnel. No more than two of these personnel shall be required to operate the shotcrete equipment.

2. Storage Space

Storage space at an FOB is at a premium. As previously mentioned, ERSF shotcrete equipment must be storable in surroundings with uncontrolled temperature and humidity, preferably outdoors. Construction of storage facilities cannot be required in support of the ERSF shotcrete equipment.

3. Training

Training of personnel who will use the shotcrete equipment must be accomplished within the existing ABO training structure, with in theater and home station training sessions. Required yearly training time cannot exceed 2 weeks.